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INTERIM REPORT NO. 6

RESEARCH AND DEVELOPMENT OF CACHE MARKER SYSTEM

PHASE II: DEVELOPMENT OF ENGINEERING PROTOTYPE

Covering the Period:

16 October 1953 to 15 December 1953

Contract No.

22 January 1954

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ABSTRACT

Field tests of the cache marker system were performed during this period. Detection of transponders buried at depths of four and five feet was obtained at horizontal distances of five and four feet, respectively. The locationsof transponders were determined to within one or two inches of their centers.

The construction of the new model of the detector incorporating the improvements suggested by the field test have been started. These improvements include a redesign of the packaging to make the detector more convenient for the operator to carry; elimination of the clock-motor-driven, rotating capacitor; and a reduction in weight of the detector.

An electronic means for obtaining frequency modulation of the oscillator, which is to take the place of the rotating capacitor, was developed during this period. This circuit is still being tested. An electro-mechanical means of obtaining the frequency modulation of the oscillator using a resonant vibrating reed is also being considered.

Temperature cycling tests of the transponders from -78°C to +80°C had no effect on the resonant frequency or the range of detectability.

Measurements were made to determine the frequency shifts of the resonant frequencies of transponders caused by having the transponders in different soils. All the soils measured, with the exception of magnetite, gave frequency shifts which were less than 0.7 kcs. The frequency shift due to pure magnetite could not be determined because it exceeded the frequency range provided by the

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measuring equipment. Additional tests are planned.

Theoretical calculations made in conjunction with experiments performed to measure the change in Q caused by a transponder at different distances from the detector show that there is an optimum size for the detector coil for a given depth of burial to transponder radius ratio.

The Detector

During this period further efforts to improve the range of detectability were unsuccessful. The circuit which was presented in Interim Report No. 5 was modified by adding an extra stage of amplification which is used as a "window" amplifier. This resulted primarily in giving a more positive indication of the transponder's presence.

We have been unable to achieve, in a portable model of the Q meter detector, the degree of sensitivity that was measured in the experiments reported in Interim Report No. 2. The high degree of stability that is required could only be attained by sacrificing some sensitivity. In these experiments the frequency of the oscillator was fixed, and the receiver circuit was adjusted to exact resonance with the oscillator frequency. The transponder was tuned, and its effect on the detector was observed with a meter indicator. Extrapolation of the data on change in Q with distance, Figure 12, shows that changes in Q of less than one part in 40,000 were being detected. In order to detect these changes in Q, the short time stability of the detection system must be at least equal to this value. This high degree of stability is not achievable in the portable model of the detector where the oscillator is being frequency modulated, and detection is achieved by moving the detector or tuning the receiver and oscillator.

In order better to utilize the range of detectability that is available, the configuration of the detector with respect to the operator was changed. In Interim Report No. 5 the detector was shown with the box containing the electronic circuits fastened in front of the operator with the detector coil about waist high, extending out in front, and parallel to the ground. This was changed to the configuration shown in Figure 1. No provision was made for folding the box containing the electronic circuits and power supply into the detector coil when not in operation, because it was considered desirable to perform the field tests at the earliest possible date.

Field Tests

On October 30, 1953, a representative of the sponsor and representatives of [redacted] conducted a field test of the cache marker system [redacted] 50X1 Virginia.

The field test consisted of burying three transponders, locating the positions of the transponders with the detector, and digging up the transponder at the indicated positions to determine how accurately their positions had been located. The horizontal ranges at which the transponders were detectable were measured. The frequency shifts of the resonant frequencies of the transponders were measured with the detector.

The transponders used for this test were resonant at 83, 98.5, and 106.3 kcs in air. The transponders consisted of a Plexiglass coil form wound with 60 turns of Litz wire made of 24 strands of No. 30 wire woven on a glass fiber core. The coil and its tuning capacitor were impregnated with a heavy coating of cerese wax and incased in Fiberglas reinforced polyester resin shell.

The site was prepared by digging holes five feet deep with a trench digger. The transponders were placed in these holes, and the holes were filled with dirt with the use of a bulldozer. Two of the transponders were buried five feet below the level of the ground and the third was buried at four feet below the ground. After the holes had been filled, the bulldozer leveled off

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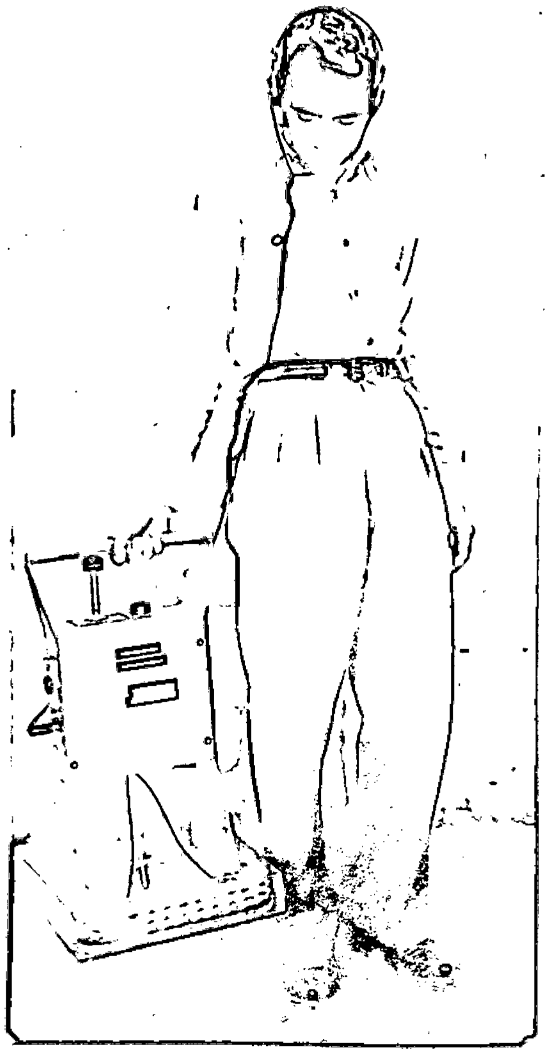

Figure 1. Model of the Detector Used for the Field Tests.

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the ground so that the locations of the holes were not discernible. Markers which had been left to locate the positions of the transponders had been shifted by the bulldozer.

The representative of the sponsor was briefly instructed on how the detector was used, and then he proceeded to locate the first transponder. He encountered some difficulty at first, for two reasons. The rotating capacitor operated intermittently, and he mixed up the use of the amplitude control and the fine tuning control. He had much less difficulty in locating the other two transponders.

The transponders buried at a depth of five feet had a horizontal range of detectability of about four feet. The transponder buried at a depth of four feet had a horizontal range of detectability of five feet. Measurements were made to determine how close the transponder would have to be approached when walking rapidly along a straight path in order to obtain a positive indication of the presence of the transponder. This information was obtained with the detector tuned to the resonant frequency of the transponder in the ground, without any further adjustment as the detector was carried along. This distance was found to be about two to two-and-a-half feet. This determines that when the detector is tuned to the proper frequency before the search is started, detection should be accomplished by walking parallel paths four to five feet apart.

The positions of the transponders, as located with the detector, were marked; and the ditch digger dug holes at these positions. It was found that the positions had been located to within one or two inches of the centers of the transponders.

The ground consisted primarily of clay and was wet due to two preceeding days of rain. The resonant frequency was lowered by the following amounts due to the increase in distributed capacity caused by the greater dielectric constant of the surrounding medium: For the 83 kcs transponder, 0.28 kcs; for the 98.5 kcs transponder, 0.30 kcs; and for the 106.3 kcs transponder, 0.48 kcs.

The sponsor's representative indicated that operation could be improved by packaging the detector so that it could be more easily carried with the detector coil parallel to the ground and by elimination of the rotating capacitor. In addition, a reduction of the weight of the detector would be desirable.

New Model of the Detector

Work on the new model of the detector, reflecting the recommendations of the sponsor's representative, was initiated during this period. The detector non-operating carrying condition is shown in Figure 2. The detector, when in this position, has been made to resemble a brief case or small suitcase. The case for this model is made of Plexiglass which is a convenient material to work with, is readily available, and makes visible the internal location and construction of components. The cases of future models will be made of molded glass fiber reinforced plastic colored to look like leather. The carrying handle in the closed position is placed above the center of gravity to make carrying easy. The detector unfolds into the operating position by holding the lid, to which is fastened the box containing the electronic circuits and batteries, opening up the case which contains the detector coil until it is parallel with the ground and bringing up the carrying handle used in the

Figure 2. View of Detector in Non-Operating Condition.

operating condition. Figure 3 shows the detector as it would be carried in the search process. In this position, the carrying handle is over the center of gravity of the detector, allowing the operator's arm to assume a natural position with the detector coil at the proper position with respect to ground. When not in use, the carrying handle used for the operating position folds in between the detector coil and the box containing the electronic circuits. Space for earphones has been provided in between the detector coil and box containing the detector circuits.

In this model of the detector the oscillator, receiver, and frequency determining circuits have been made as separate units which fit together in a minimum space.

The side of the detector that is carried next to the operator is shown with the cover removed in Figure 4. The four tubes and their shields, located in about the center of the photograph, are in the receiver circuit. The filament batteries, to the left and at the bottom, supply the filament voltages for this circuit. They are located so as to provide the shortest possible leads to the filaments. This is necessary in order to reduce feedback among the various filaments which are all operated at different potentials with respect to ground. The two B batteries, located at the top, supply the plate voltage for the oscillator and receiver circuits and the bias required for the input stage "window" amplifier. The oscillator circuit, with its own chassis, is located at the right side. Figures 5 and 6 show two views of the oscillator chassis. The first is a top view of the oscillator chassis which shows its separate filament battery, tube and shield, and circuit components for obtaining bias for the grid circuit and filtering of the plate circuit to

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Figure 3. View of the Detector in the Operating Condition.

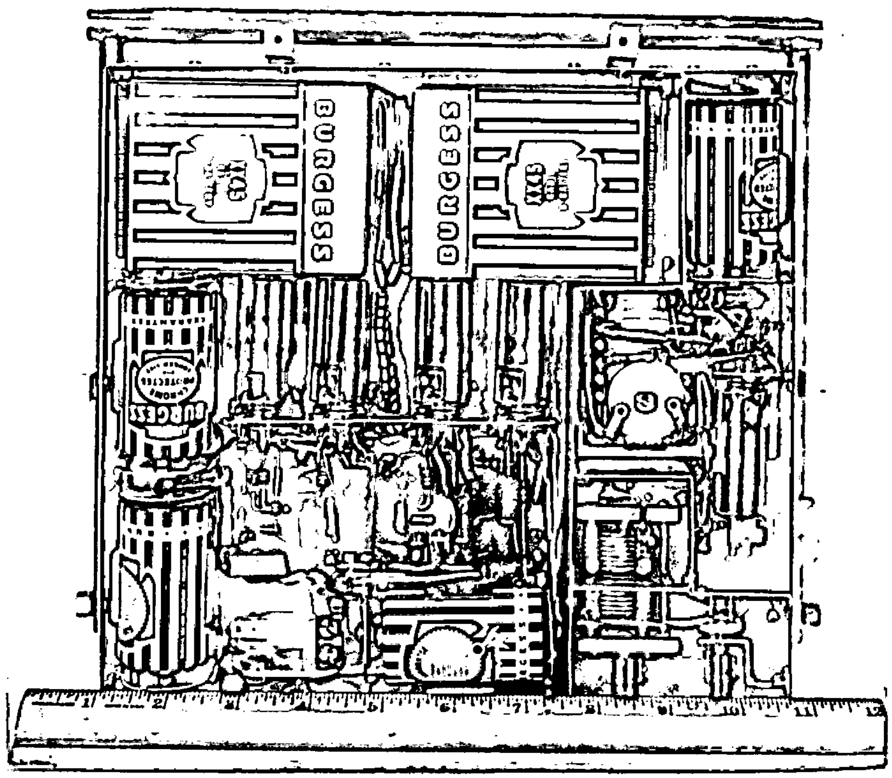

Figure 4. View of Box Containing the Electronic Circuits of the Detector.

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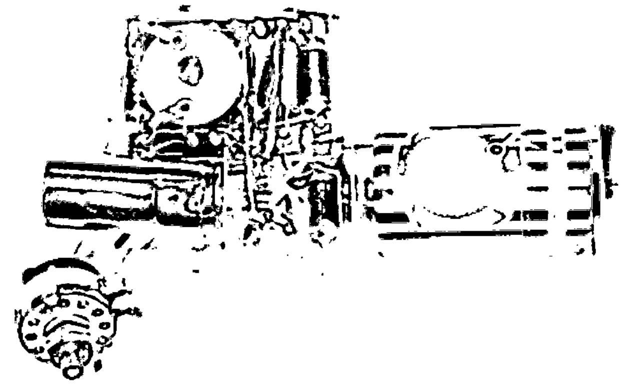

Figure 5. Top View of Oscillator Chassis.

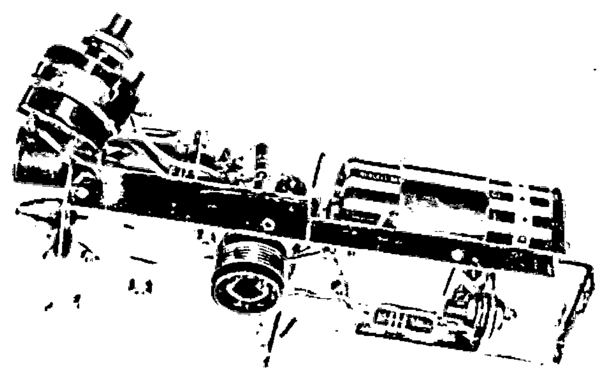

Figure 6. Bottom View of Oscillator Chassis.

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prevent interaction with the receiver circuit through the common plate voltage supply. The bottom view shows the oscillator coil which is actually a powdered iron core transformer. The outside winding which matches the output of the oscillator to the impedance of the series resonant circuit is visible in Figure 6.

The other side of the box containing the detector circuits, shown in Figure 7, gives a view of the forty variable capacitors which are used to adjust the frequencies of the oscillator and receiver circuits to coincide and track over each of the ten bands. Four of these variable capacitors are used for each band, two for the oscillator circuit and two for the receiver circuit. The vacant space in the center is reserved for the band switch which will be a four-deck, ten-position, rotary switch. This switch will connect the proper variable capacitors to the two sections of the main tuning capacitor which can be seen in the lower right corner of Figure 4.

Elimination of the Rotating Capacitor

The erratic operation of the rotating capacitor during the field tests has indicated that a more satisfactory means of accomplishing frequency modulation of the oscillator in the detector is needed. The original choice of the clock-motor drive was based on finding a source of power that did not require batteries. In view of the small amount of power that is required by the detector, an electronic or electro-mechanical device which would not require an increase in the size of the batteries that are already used would be desirable if more dependable operation resulted.

Frequency modulation of an oscillator can be obtained by using a reactance tube modulator. This can be accomplished without the use of an

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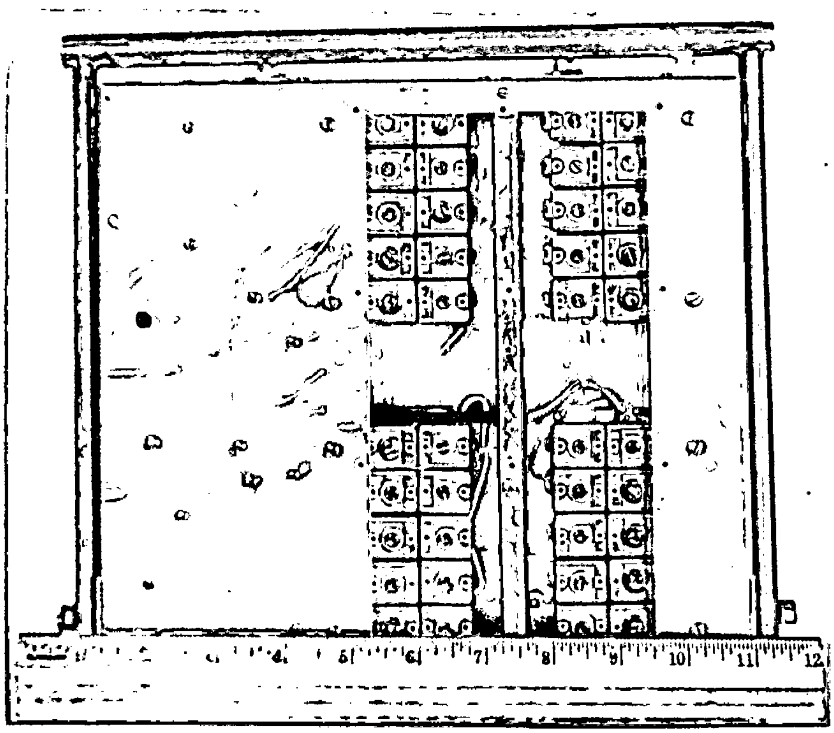

Figure 7. View of Box Containing Detector Circuits Showing Adjustable Capacitors of Frequency Determining Circuit.

additional tube by substituting a type 3A5 for the 3V4 that is presently being used in the oscillator circuit. The type 3A5 vacuum tube is a twin triode designed for battery operation. One of the triodes can be used for the oscillator, and the other triode can be used for the reactance tube modulator.

The circuit shown in Figure 8 was built to determine whether it would perform the same function as the rotating capacitor. The circuit functions as follows: the triode to the left operates as a Hartley oscillator with L (1) and C (1) being the frequency determining components. R (1) and C (2) develop the bias for the oscillator. The bias for the reactance tube which is the right-hand triode is obtained from the oscillator current flowing through R (5) and by grounding the control grid through R (2). The proper phase between plate voltage and plate current, so that the tube will appear as a capacitive reactance, is obtained by C (5), connected between plate and grid, and R (2) between grid and ground. R (2) also serves as a load across which the modulating voltage to drive the reactance tube is developed. A relaxation oscillator consisting of R_7, C_8, and a neon bulb, NE_2, is used as a source of the modulating signal. C (4) couples the variation of capacity across the frequency determining circuits of the oscillator. R (6) was put in to reduce the drive to the reactance modulator and prevent clipping caused by the flow of grid current. R_3 and C_6 decouple the oscillator from the common B^+ supply.

The tube appears as a capacitive reactance because the current is not 180 degrees out of phase with the a.c. plate voltage. As the plate current is varied according to the change in grid voltage, the plate resistance of the tube also varies, causing a varying resistive component as well as a varying

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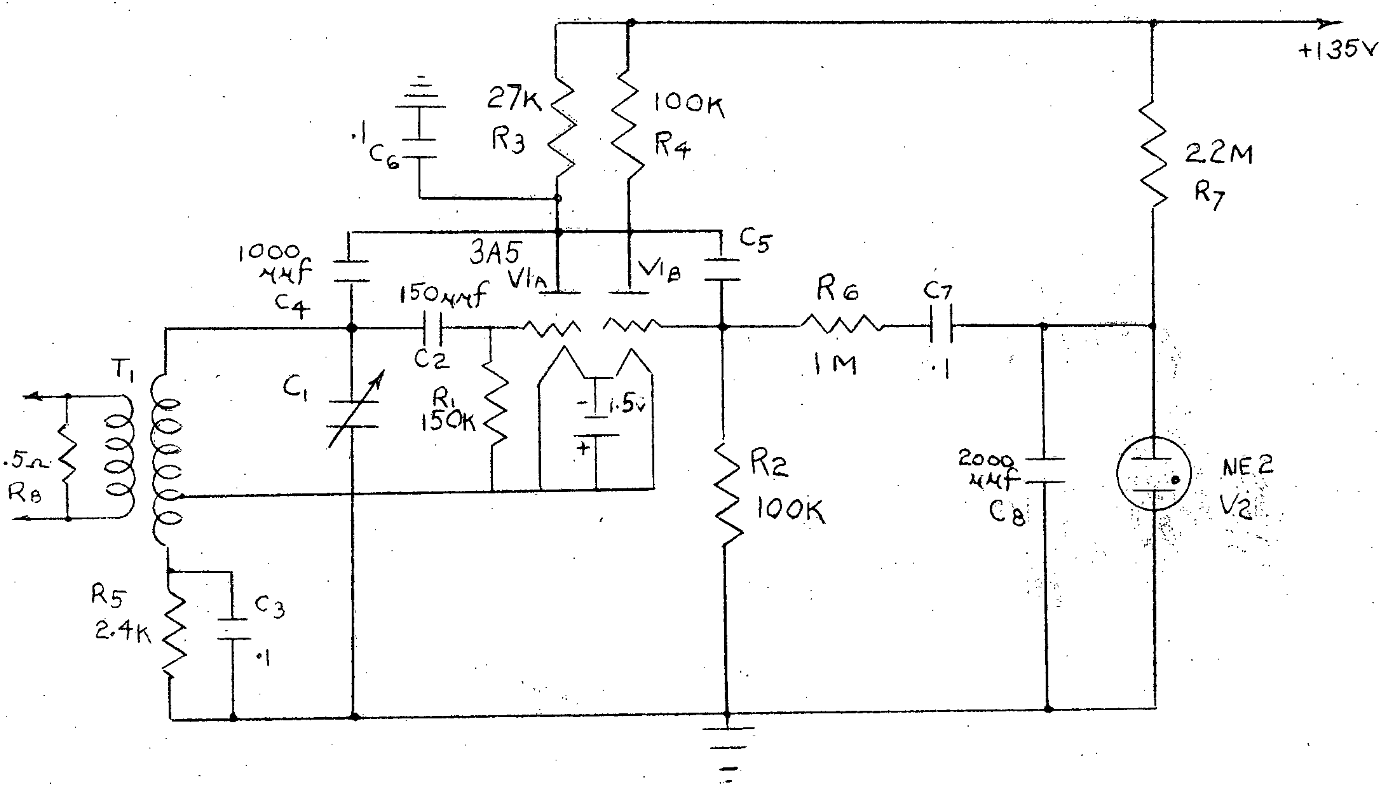

Figure 8. Reactance Tube Modulated Oscillator

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reactive component of impedance to be reflected back to the oscillator. The result is amplitude modulation as well as frequency modulation. The percentage of amplitude modulation appears to depend on the amount of frequency modulation, which is determined by the coupling capacitor C (4) and the C (5) of the phase determining circuit. By reducing the value of either of these capacitors, the percentage amplitude modulation is reduced with a corresponding reduction in frequency shift. The frequency shifts were measured by applying different values of d.c. bias to the modulator grid and measuring the corresponding frequencies. The maximum frequency shifts obtained were 2 kcs with a corresponding variation in amplitude of one part in thirty. Experiments will be performed to determine whether this variation in amplitude can be tolerated in the detector.

Another system which is being considered as a means of eliminating the rotating capacitor consists of a vibrating resonant reed driven by an electro-magnet. The capacity variations would be obtained by placing the vibrating reed between two fixed plates and using the reed as one conductor and the two plates, electrically connected together, as the other plate of the capacitor. Calculations show that plates 1" x 1/2" and a reed vibrating with a maximum displacement of 0.005 inches can readily give 10 $\mu\mu$f capacity changes. Work on this system will be continued.

Other Systems

Some experiments were performed to test the practicability of a simple form of detection system shown in Figure 9.

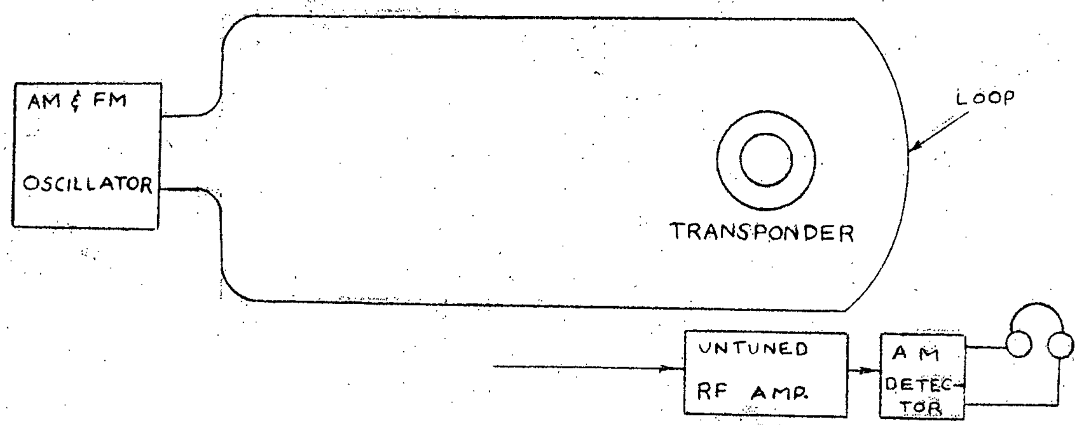

Figure 9. Simple Detection System

The oscillator generates a radio frequency signal which is amplitude modulated at an audio frequency. A rotating capacitor is used to sweep the frequency of the oscillator by plus and minus 3 kcs and passing through the natural frequency of the transponder. The rate of the rotating capacitor is such as to cause modulation at a very low frequency. The oscillator drives a one-turn insulated wire loop laid on the ground, enclosing the area in which the transponder is believed to be located.

The detector consists of a three foot length of wire feeding an untuned RF amplifier followed by an AM detector and phones.

The detector, which cannot detect the FM portion of the signal, will give a steady signal when in the vicinity of the loop but not in the vicinity of the transponder. The transponder, which is a very high Q resonant circuit, demodulates the FM portion of the signal from the oscillator. If the detector is brought in the vicinity of the transponder, a pulsating audio signal will

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be heard due to the reradiated energy as the oscillator sweeps through the resonant frequency of the transponder.

In the first test a single loop of wire was strung around the room at a height of about six feet above the floor. With this arrangement, the range of detectability was only 18 to 24 inches.

In a second test untuned loops, about 18 inches in diameter, were used as antennas with the oscillator and detector, respectively. With this arrangement somewhat greater range, four feet, was obtained; but direct coupling between the oscillator and receiver coils introduced difficulties which could not be controlled. The above system was abandoned.

Another experiment was made using the same arrangement as in Figure 9, except that audio frequency amplitude modulation was not used. The FM modulation should have been heard in the phones when the detector was in the vicinity of the transponder. However, the oscillator paralyzed the receiver and thus swamped the weaker signal coming from the transponder. No further work was done on this system.

Temperature Cycling of Transponders

A temperature cycling test was performed on two incased transponders. The test consisted of cycling the transponders from -78°C in dry ice to +80°C in an oven. The detectability and frequency of the transponders were measured at the high and low temperatures for each cycle. No change in the range of detectability was observed during the temperature cycling process. The resonant frequencies of the transponders, which were measured before and after each of the two temperatures, are given in Table 1. The transponders were at each temperature for one hour before cycled. Frequency shifts occurred only for the second and third cycle, this being attributed to inaccuracies in the measuring system. One transponder remained in the dry ice for fifteen hours with no resulting change in frequency or change in range of detectability.

Table 1

Cycle	Transponder	Frequency in kcs. at $-78^{\circ}C$	Frequency in kcs. at $+80^{\circ}C$
1	2	98.48	98.48
	3	82.48	82.48
2	2	98.45	98.43
	3	82.69	82.58
3	2	98.36	98.36
	3	82.65	82.58
4	2	98.48	98.48
	3	82.42	82.42
5	2	98.48	98.48
	3	82.48	82.48

Table 1. Transponder Temperature Cycling

Effects of the Surrounding Medium on the Transponder

The change in the ability to detect the transponder when buried, as compared to the ability to detect the transponder in air, depends on the electrical properties of the medium in which it is buried. The electrical properties of the medium change the electrical properties of the transponder, and they also affect the attenuation of the signal through the medium. Experiments and calculations indicate that the reduction in signal due to these propagation losses can be neglected. However, the changes in the electrical properties of the transponder cannot be neglected since they cause a change in the resonant frequency of the transponder. They may also cause a change in the Q of the transponder; but, with the exception of salt water, this has not been observed in any of the media that we have tested. The changes in frequency are caused by the change in distributed capacity due to the dielectric constant of the surrounding medium in which the transponder is buried, being different than that in air, and by the change in inductance caused by the magnetic susceptibility of the surrounding medium, being different than that of air.

Some experiments have already been performed to determine the magnitude of the frequency shifts that can be expected. These experiments and their results are discussed below.

In order to determine the effect the medium surrounding the transponder has on the resonant frequency of the transponder, measurements of the resonant frequencies of four transponders in air and sand were made. The transponders were identical except for the value of fixed capacity that was connected across the coil inside the transponder shell. The resonant frequencies of the transponders, as measured in air, varied from 82 to 143 kcs with corresponding fixed capacitors ranging in values from 2200 to 680 $\mu\mu$f.

The experiment consisted of measuring the frequency of a transponder in air and then in a large box of sand using the detector as the frequency measuring device. At the same time, any change in detectability could also be observed. The frequencies of the transponders in air and in sand are given below:

Frequency (in air)	Frequency (in sand)	Frequency Shift
110.5	110.1	0.4
98.5	98.11	0.39
82.51	82.30	0.21

The transponder which measured 143 kcs in air could not be detected in sand with the detector. This was originally attributed to the lowering of the Q of the transponder by the lossy capacity added by the sand. This effect was not observed with the other transponders which we believed was due to the larger amounts of fixed capacity that are used on the lower frequencies where percentage of lossy capacity is considerably smaller. Calculations of the amount of capacity that is added by the sand, because of the higher dielectric constant of sand, indicate that the Q could not have been altered sufficiently at 143 kcs without also being altered at the lower frequencies. The frequency shift at 143 kcs was great enough to bring the frequency out of the band, and a reading could not be taken.

The frequency shifts increase with frequency, and in order to limit the size of the bands on the higher frequencies an upper limit of about 105 kcs has been chosen. The lower limit of 80 kcs has been chosen to limit the amount of capacity needed to resonate the detector coil to the transponder frequency since the inductance of the detector coil is determined by its geometry and is not variable.

Measurements on Sand Itself

In an effort to correlate the results of these measurements in sand to results that might be expected in various types of soil, a soil capacitor was constructed to measure the dielectric constant of sand. With this value and other dielectric constants for various other soils found in the published literature* it is possible to determine the approximate shifts that are to be expected.

*C. A. Heiland, <u>Geophysical Exploration</u>, Prentice-Hall Inc., New York, pp. 666-667.

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The soil condenser consisted of two concentric cans approximately four inches in length and having diameters of four and two-and-one-half inches, respectively. The dielectric constant of the sand was determined by the ratio of the capacity measured with and without sand. For the sand used in determining the frequency shifts given above, the dielectric constant measured to be 4.9 and 4.5 for two runs.

The moisture content of the sand used in these tests was not readily obtainable. However, the resistance readings between the terminals of the condenser for two runs measured 130,000 ohms and 242,000 ohms, respectively.

Another test consisted of measuring the capacity of the soil condenser and varying the moisture content. Here again the amount of moisture present was necessarily small since the capacity could not be determined when the moisture content lowered the Q appreciably, and accurate measurements using the Q meter could not be made. Because of the small amounts of moisture present, the capacity was measured as a function of resistance between terminals. A plot is shown in Figure 10. The point on the curve represented by 98 μμfd and 800,000 ohms was obtained using dry sand. The point corresponding to 135 μμfd and 30,000 ohms was obtained with sand having enough moisture content to pack. A point not shown on the curve gave 45 μμfd with a resistance of 20 megohms using sand baked in an oven.

It appears from Figure 10 that, if the moisture content of the sand were increased sufficiently, the dielectric constant would approach that of water.

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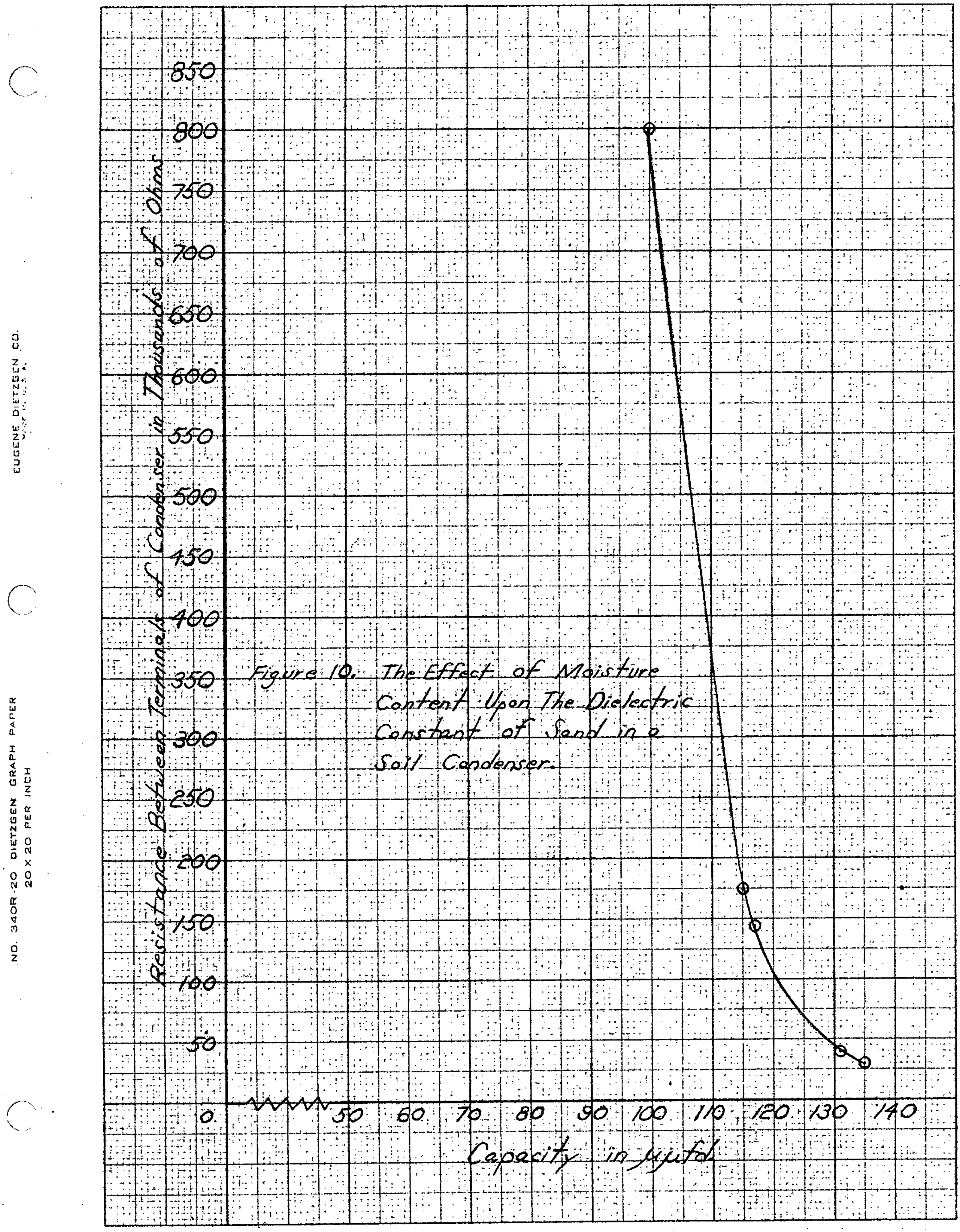

Figure 10. The Effect of Moisture Content Upon The Dielectric Constant of Sand in a Soil Condenser.

In a further attempt to determine transponder frequency shifts occurring in various materials, additional measurements were made in pave, sand, fine gravel, coarse gravel, and magnetite. The results of these tests for the first four materials are listed in Table 2. The shifts in the magnetite exceeded the limit of the bands to which the detector was tuned, and it was not possible to determine the frequency shifts for this material. This material is being made available at the laboratory and further tests to determine the frequency shifts caused by magnetite will be made. It is presently believed that the shifts were in excess of 4 kcs for the transponders tuned to 98 and 82 kcs.

Table 2. Transponder Frequency Shifts in Various Materials

Transponder	Material	Frequency in Air in kcs.	Frequency in Sand in kcs.	Frequency Shift in Cycles
2	Pave	98.420	97.810	610
3	Pave	82.460	82.100	360
2	Sand	98.450	98.170	280
3	Sand	82.510	82.340	170
2	Fine Gravel	98.450	98.110	340
3	Fine Gravel	82.540	82.300	240
2	Coarse Gravel	98.450	98.300	150
3	Coarse Gravel	82.540	82.400	140

The above results are the average of three sets of readings taken by three observers. Since most of the individual readings differed by only two or three points, and because the calibration of the dial from which these readings were taken had limited accuracy, the measured shifts are believed to be accurate to only ±50 cycles.

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Some Basic Theory of Coupled Circuits

An examination of the equations which describe the mutual inductance between two parallel coils has resulted in the determination of an optimum size for the detector coil for a given transponder diameter and depth of burial. This study has also made available the relation between range of detectability and stability in terms of the fractional change in amplitude that must be measured in order to detect the transponder for any distance.

The change in Q caused by a tuned circuit was measured with the Boonton Q meter for a number of distances between the coil connected to the Q meter and the tuned circuit. These measurements were made with the Q meter and the tuned circuit tuned to the same frequency. The results of these measurements are shown in Figure 11. In order to determine how the change in Q behaves as a function of distance, these data were plotted on loglog paper. If it is assumed that the change in Q is proportional to 1/c raised to some power, where c is the distance between the coils, then the slope of the curve obtained by plotting the data on loglog graph paper is the value of this power. Figure 12 shows the data replotted on loglog graph paper where it can be seen that the slope is not a constant for small values of c. For values of c larger than 4.5 feet the slope remains constant and corresponds to the sixth power. This is the value which is expected from previous consideration of how the mutual inductance varies with distance. The curve has been extrapolated so that values for the change in Q at large values of c could be obtained.

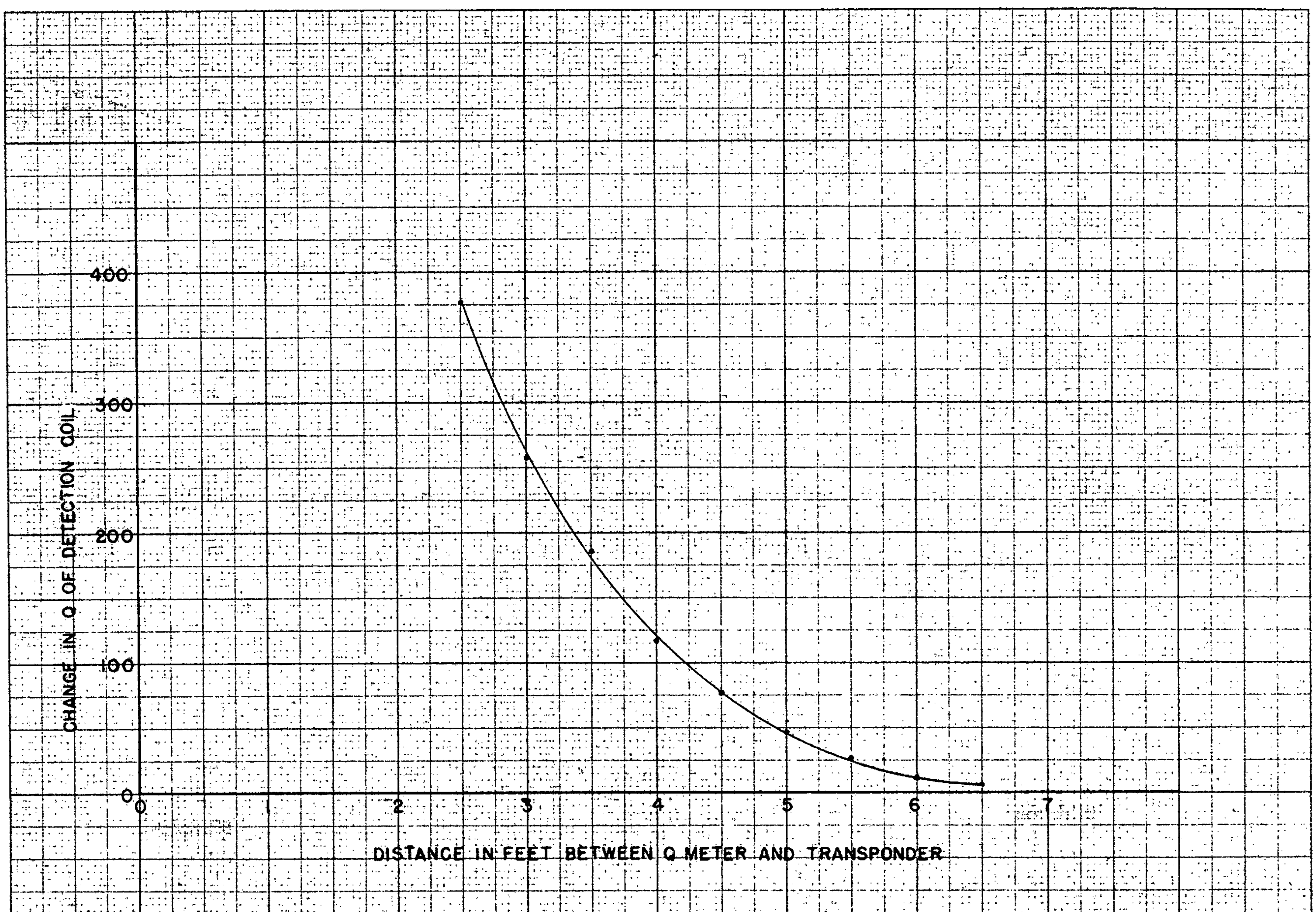

Figure 11. Linear Plot of Change of Q as a Function of Distance Between Transponder and Detector Coil

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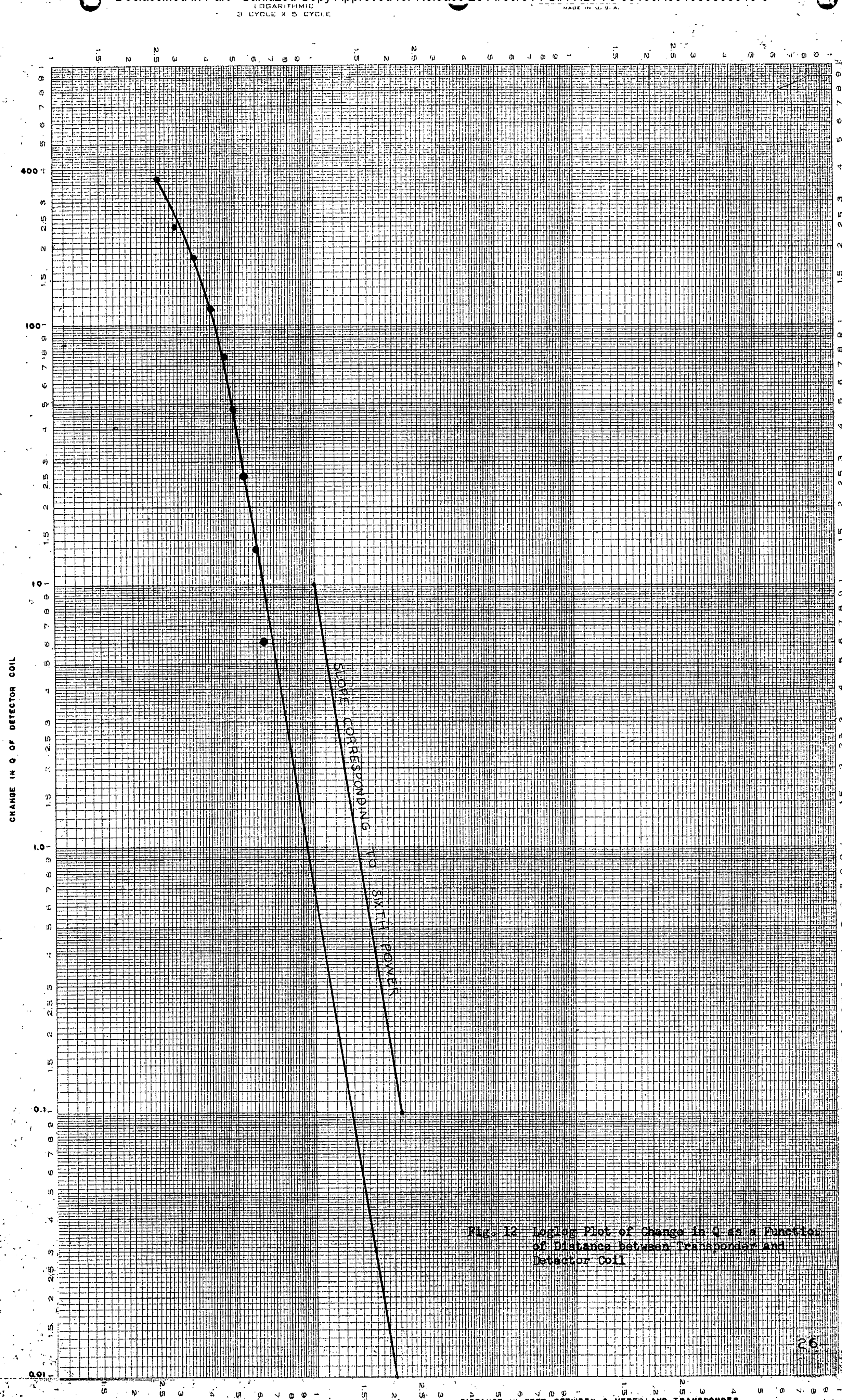

Fig. 12 Loglog Plot of Change in Q as a Function of Distance between Transponder and Detector Coil

The equation describing the mutual inductance without any approximations is:

$$L_{ab} = \frac{1}{2} \mu_o \, ab \int_0^{2\pi} \cos\theta \, (c^2 + a^2 + b^2 - 2ab\cos\theta)^{-\frac{1}{2}} \, d\theta \quad *$$

where L_{ab} is the mutual inductance between two coils whose radii are a and b

μ_o is the permeability of the surrounding medium

c is the distance between centers of the two coils

and θ is the best defined by Figure 13.

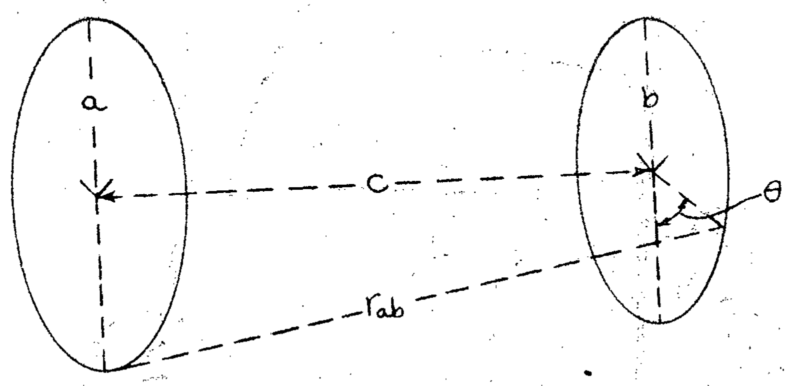

Figure 13. Geometry of Coils Used in Calculation of Mutual Inductance.

L_{ab} is an elliptic integral and can be written as:

$$L_{ab} = \mu_o (ab)^{\frac{1}{2}} \left[\left(\frac{2}{k} - k\right) K - \frac{2}{k} E \right]$$

where $k^2 = 4ab \left[(a + b)^2 + c^2 \right]^{-1}$ and K and E are the elliptic integrals

$$K = \int_0^{\pi/2} \frac{d\phi}{(1 - k^2 \sin^2 \phi)^{\frac{1}{2}}} \quad \text{and} \quad E = \int_0^{\pi/2} (1 - k^2 \sin^2 \phi) \, d\phi$$

*G. P. Harnwell, Principles of Electricity and Electromagnetism, McGraw-Hill Book Company, Inc., 1938, p. 304.

which have been evaluated for different values of k in the literature.* For c   a and b

$$L_{ab} \approx \frac{\mu_o \pi}{16} (ab)^{\frac{1}{2}} k^3 \qquad \text{and}$$

$$k^2 \approx \frac{4ab}{c^2}$$

Then $$L_{ab} \approx \frac{\mu_o \pi}{16} (ab)^{\frac{1}{2}} \left(\frac{4ab}{c^2}\right)^{3/2}$$

or $$L_{ab} \approx \frac{\mu_o \pi}{2} \frac{(ab)^2}{c^3}$$

The change in Q due to the tuned circuit is proportional to the mutual inductance squared, $(L_{ab})^2$, and for the conditions $c \gg a$ and b varies as $(1/c)^6$.

The value of $L_{ab}/\sqrt{ab}$ is completely defined by the value of k. Keeping this in mind, consider a graph where $X = \frac{a}{b}$ and $Y = \frac{c}{b}$ and constant k lines are plotted. To see what this gives, we write:

$$\frac{1}{k^2} = \frac{(a + b)^2 + c^2}{4ab} = \frac{a}{4b} + \frac{b}{4a} + \frac{1}{2} + \frac{c^2}{4ab}$$

or $$4\left(\frac{1}{k^2} - \frac{1}{2}\right) = \frac{a}{b} + \frac{b}{a} + \frac{c^2}{ab}$$

In terms of X and Y

$$4\left(\frac{1}{k^2} - \frac{1}{2}\right) = X + \frac{1}{X} + \frac{Y^2}{X}$$

which can be rewritten as

$$\left[X - 2\left(\frac{1}{k^2} - \frac{1}{2}\right)\right]^2 + Y^2 = \frac{4}{k^2}\left(\frac{1}{k^2} - 1\right)$$

which is the equation of a circle of radius $\frac{2}{k}\left(\frac{1}{k^2} - 1\right)^{\frac{1}{2}}$ whose center is on the X axis located at $2\left(\frac{2}{k^2} - \frac{1}{2}\right)$.

*Charles D. Hodgman, M.S., Handbook of Chemistry and Physics, Chemical Rubber Publishing Company, 34th Edition, 1952-1953, pp. 234-236.

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These circles connect points of equal value, $L/\sqrt{ab}$.

Now $$\frac{L}{\sqrt{ab}}\sqrt{\frac{a}{b}} = \frac{L}{b}$$

so that if we multiply $\frac{L}{\sqrt{ab}}$ by $\sqrt{X}$, $\frac{L}{b}$ can be evaluated along each of the circles. The curves for constant $L/\sqrt{ab}$ and $\frac{L}{b}$ are shown in Figure 14.

Now consider a line of constant value of Y, tangent to one of the constant $\frac{L}{b}$ curves. This point of tangency gives the value of X for the given value of Y for which L/b is a maximum. In terms of a, b, c this point specifies the values for $\frac{c}{b}$ and $\frac{a}{b}$ for which $\frac{L}{b}$ is a maximum.

Thus, for a transponder of radius b buried at a depth c below the surface of the ground, a detector coil of radius a will give the largest indication of the presence of the transponder.

A curve connecting these points of tangency gives the optimum radius of the detector coil for any given size transponder buried at any depth. If this curve is labeled as 100% to indicate the percentage of signal from the transponder, then curves indicating lesser percentages of maximum signal can be obtained. The curves for 80% and 50% are indicated in Figure 14. They show that the increase in signal is not proportional to the increase in area of the detector coil.

Unfortunately, the region in which we are normally interested is where X is in the neighborhood of one or two, and Y has values of two to five. In this region the curves for constant k and constant L/b converge and additional work would be required to expand this region. In this region the

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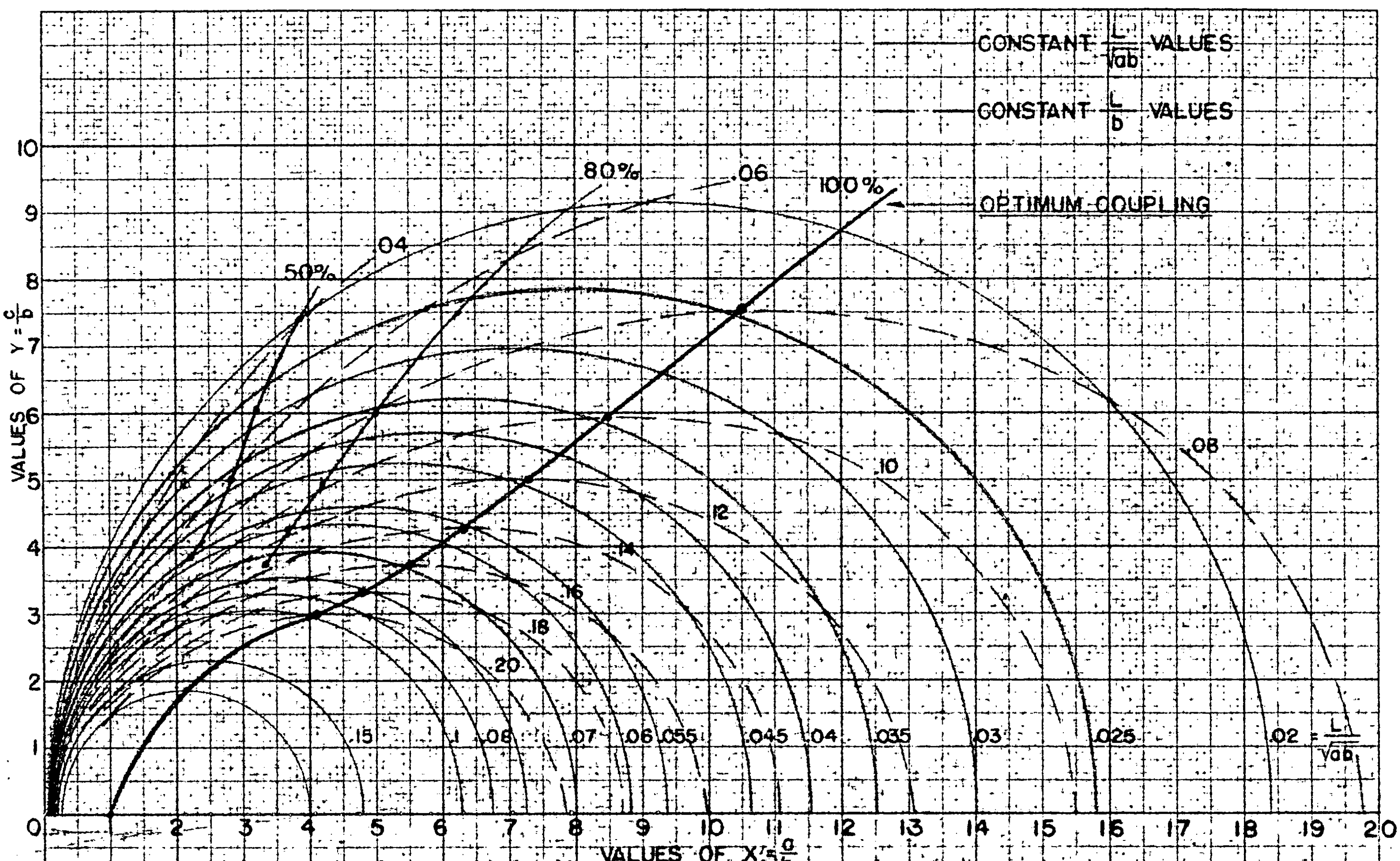

FIG. 14 FAMILY OF CONSTANT K CURVES SHOWING CURVES OF CONSTANT $\frac{L}{b}$ AND CURVE FOR OPTIMUM COUPLING

percentage of optimum coupling is estimated to be only about five per cent. Improvement in the coupling of the detector can only be accomplished by increasing the size of the detector coil or size of the transponder.

Program for the Next Interval

1. The work on developing a circuit to replace the rotating capacitor will be completed and installed in the final model of the detector.

2. It is expected the band switch will be received during this interval and will be tested and installed.

3. The final model of the detector will be completed and additional testing will be carried out.

4. Experiments will be carried out to determine whether the sizes of the batteries that are presently being used are sufficient to run the detector continuously for four hours at zero degrees Fahrenheit.

5. Tests will be made to determine the range of detectability of the detector with the transponder immersed in sea water.

6. The preparation of the final report will begin.